Clinical application of ultrashort echo-time MRI for lung pathologies in children

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Pictorial Review

Clinical application of ultrashort echo-time MRI for lung pathologies in children

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Lung magnetic resonance imaging (MRI) is considered to be challenging, because the low proton density of the tissue, fast signal decay, and respiratory artefacts hamper adequate image quality. MRI of the lungs and thorax is increasingly used in the paediatric population, because it is a radiation-free alternative to chest CT. Recently, ultrashort echo-time (UTE) sequences have been introduced into clinical MRI protocols, in order to improve the contrast-to-noise ratio due to reduced susceptibility artefacts and to depict structural alterations comparable to CT. The purpose of this review is to provide an overview of various clinical conditions and pathologies in the paediatric chest depicted by an UTE sequence, the so-called three-dimensional (3D) Cones sequence, in comparison with conventional MRI sequences. Besides describing typical features of cystic fibrosis, we present UTE application in other more or less common paediatric lung pathologies, for instance, interstitial pneumopathies, pulmonary infections, and congenital pulmonary malformations.

Introduction

Lung MRI has become widely available for the paediatric population in recent years and has been shown to be able to visualise general pathologies, such as consolidation, bronchiectasis, bronchial wall thickening, or mucus plugs in patients with cystic fibrosis.[1–3] Other potential applications for lung MRI as an alternative to CT are evaluation of complicated pneumonia, congenital lung malformations, or tumours as well as monitoring of lung disease in children.[1–5]

Due to low proton density with an associated low signal, i.e., the low signal-to-noise ratio (SNR) and susceptibility artefacts at air–tissue interfaces, detailed imaging of the parenchymal structure is challenging when using conventional MRI sequences.[6–8] An increase in SNR can be

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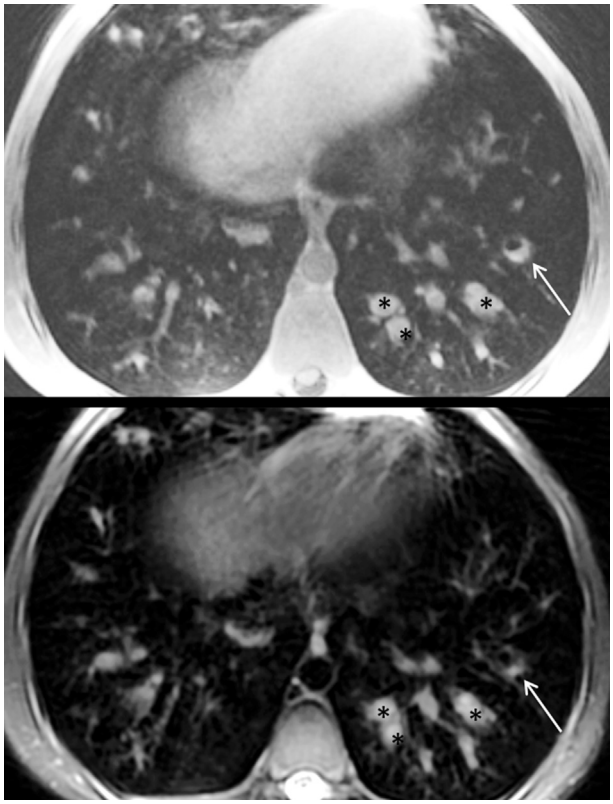

Figure 1 A 14-year-old female patient with cystic fibrosis. Axial UTE (upper row) and T2-weighted radial FSE (lower row) images show complete (black asterisks) or incomplete (white arrows) mucus obliteration in dilated bronchi in both lower lobes, predominantly in the left lower lobe.

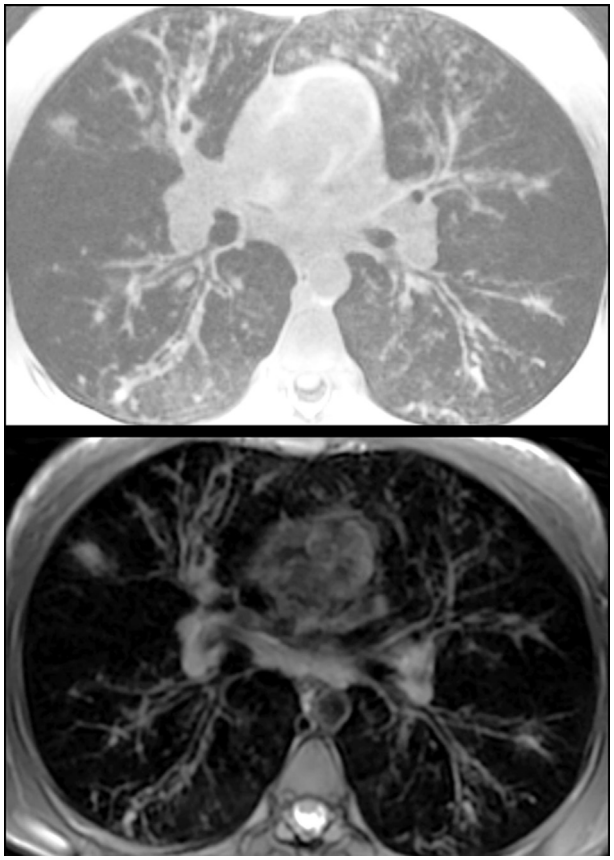

Figure 2 A 14-year-old female patient with cystic fibrosis and cylindrical bronchiectasis in both lungs. The extent of bronchiectasis is shown on UTE (at the top) and fat-saturated T2-weighted radial FSE sequence (at the bottom). Thickness of the bronchial walls is best assessed on the UTE images.

achieved by signal averaging; however, this is limited by a suitable length of acquisition time in the clinical routine.[9]

In general, lung pathologies leading to an increase in protons in terms of "plus" pathologies are easier to visualise by conventional MRI sequences than pathologies with loss of tissue and increase of airspace, described as "minus" pathologies.[7] In addition, the lungs are affected by respiratory and cardiac motion, which result in pronounced motion artefacts in the form of ghosting and blurring, dependent on the acquisition scheme.[10] Imaging can be performed during a breath-hold of typically <20 seconds duration, either in end-expiration or in full inspiration, or during free breathing by using respiratory triggering and gating, in order to acquire images at defined stages during respiration.[9] In the paediatric setting, there is the need for sedation or general anaesthesia in many cases; furthermore, optimised protocols using sequences with motion correction or respiratory triggering should be applied.[5,11] Care should be taken to obtain high image quality, which may be hampered by dorsobasal atelectases due to sedation.

There are several standard MRI sequences currently used for paediatric lung imaging[2,5,11]: balanced steady-state free precession (bSSFP) and single-shot fast spin echo sequences (SSFSE), which are fast and robust sequences that do require breath-holding. They are excellent to get a general overview of the chest pathology and are appropriate for depicting pulmonary diseases with high water content as a consequence of their inherent T2-weighting, for example, fluid-filled congenital cystic malformations or pathologies associated with cystic fibrosis. Other more time-consuming sequences with respiratory gating, such as T2-weighted fat-saturated sequences with radial k-space filling (PROPELLER technique) or proton density (PD)-weighted fast spin echo (FSE) sequences, allow for improved visualisation of the lung structure as a result of higher spatial resolution and less respiratory artefacts.[12] The T2-weighted sequence should be used with fat saturation in order to reduce potential artefacts from bright fat of the chest wall.

Fast spoiled gradient echo (FSPGR) or FSE sequences with T1-weighting can be applied before and after contrast medium administration. Perfusion imaging with a dynamic 3D gradient echo sequence (TRICKS) can be added to the MRI protocol.[13,14]

Although these sequences work well in pulmonary diseases with increased signal in the lung tissue or in fluid collections, they are not sufficient in the opposite case.[7] The extremely short T2* of the lung demands a fast signal acquisition following excitation before the signal decays into the noise level.[8] Conventional sequences do not have

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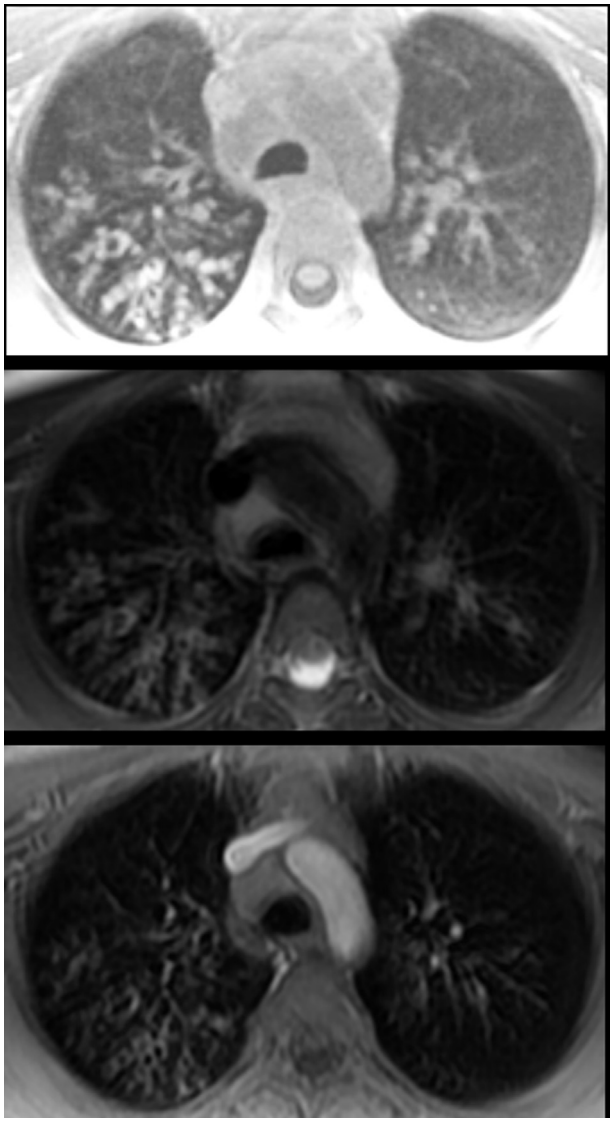

Figure 3 Axial images at the level of the carina in an 11-year-old female patient with cystic fibrosis. The UTE (upper row), the fat-saturated T2-weighted radial FSE (middle row), and the contrast-enhanced T1-weighted gradient echo images with breath-hold (lower row) reveal the severely affected upper segment of the right lower lobe showing pronounced tree-in-bud pattern as well as bronchiectasis.

short enough echo times to receive the signal before its decay. Particularly in lung diseases with reduced signal intensity and distorted parenchymal structure ("minus" pathologies), it is challenging to visualise the pulmonary microstructure and pathologies adequately and equivalent to CT.

The principles of ultrashort echo time (UTE) and zero echo time (ZTE) sequences were developed more than two decades ago.[15,16] They have experienced a revival some years ago in the course of technical development in scanner hardware, in software progress and sequence optimisation. Currently, different types of UTE and ZTE sequences have found their way into clinical application[17–20]. They distinguish themselves from conventional MRI sequences by

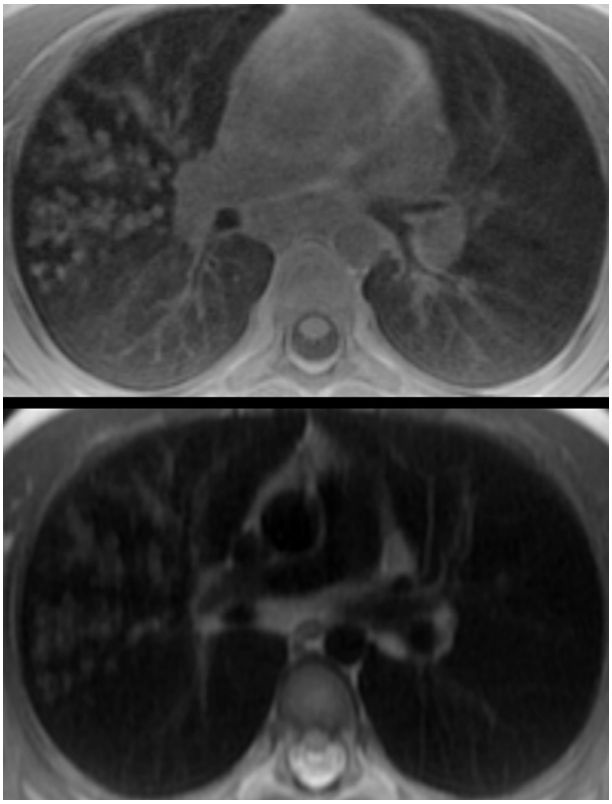

Figure 4 Axial images through the middle and lower lobes in an 11-year-old female patient with cystic fibrosis. Tree-in-bud alteration and mild bronchiectasis in the middle lobe is more clearly depicted on the UTE (at the top) than on the SSFSE sequence (at the bottom) revealing a blurry appearance of the structural changes.

having extremely short echo times, which makes them suitable for their application in lung imaging.[10,21,22] UTE and ZTE have recently been considered as "game changers" for lung MRI by the Fleischner Society.[23]

3D UTE sequences use a hard, non-selective pulse (minimum phase SLR slab-selective pulses are available as well) in the order of some microseconds, followed by a centre-out readout, i.e., going from the centre of k-space outward in a radial trajectory.[7,24] 3D UTE is superior to 2D UTE, as it provides higher and isotropic spatial resolution with complete chest coverage and less motion artefacts. ZTE takes the UTE implementation even further, achieving shorter echo-times by employing a switched-on reading gradient during radiofrequency excitation. A non-selective hard pulse excitation and constantly on readout gradients are characteristic. As readout gradients do not need to be switched off after each readout, ZTE results in silent and faster acquisitions.[7,10] It comes inherently with PD-weighted contrast.

3D Cones is a three-dimensional UTE sequence using a twisting radial k-space trajectory to produce images with TE of $\geq$28 μs (GE Healthcare).[24] It includes an extended alternative version to 3D projection reconstruction where the spokes twist around one of the axes, which results in shorter scan times with increased SNR. If extra twisting is added to the spokes, the readout of each spoke takes longer, but the filling of k-space is more efficient and faster, and

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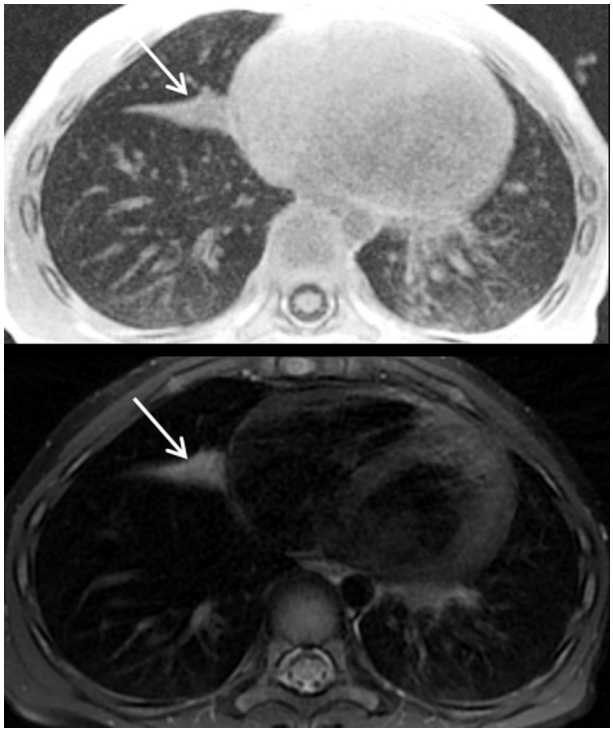

Figure 5 A 4-year-old female patient with cystic fibrosis. The consolidation (arrows) in the middle lobe is evident on UTE (upper row) and fat-saturated T2-weighted radial FSE (lower row). Peripheral lung markings are better visualised by the UTE sequence.

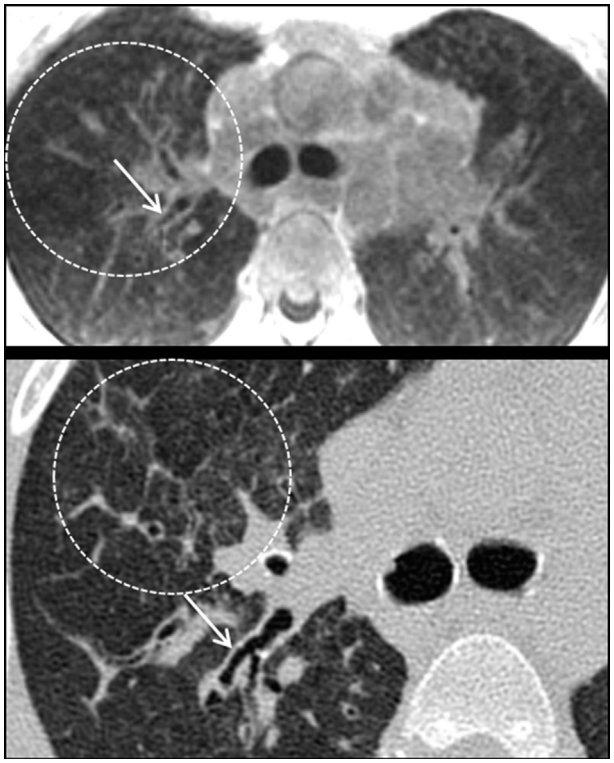

Figure 6 A 14-year-old female patient with interstitial pneumopathy. Axial UTE sequence shows mild bronchiectasis and bronchial wall thickening (arrows), increased visibility of the central and peripheral interstitium with interlobular septa and architectural distortion (dotted circle). These structural parenchymal changes are depicted equivalent to the axial CT image (at the bottom).

thus achieving overall shorter scan times.[24] The total number of cones and interleaves of the acquisition depend on both field of view (FOV) and resolution. An isotropic spatial resolution with full chest coverage resulting from a large FOV similar to CT is achieved. The images shown in this review were acquired using a 1.5 T machine with a section thickness of 2–3 mm. The in-plane resolution was 1.3 mm for all figures. 3D Cones cannot be performed in a single breath-hold; therefore, respiratory gating is necessary, which results in acquisition times of about 5 minutes. Owing to its inherent three-dimensionality, the 3D Cones sequence can be reformatted in multiplanar orientations, which improve the localisation assessment. 3D Cones is able to quantify age- and gravity-dependent lung intensity in children comparable to lung density described in CT studies.[25]

This review illustrates various clinical applications of UTE lung MRI in the paediatric population. We demonstrate the potential and spectrum of the 3D Cones sequence for depicting lung pathologies in congenital and acquired pulmonary diseases in comparison to conventional lung MRI sequences.

Cystic fibrosis

Cystic fibrosis is the most common genetic disease in Europe with chronic progressive lung disease as the main cause of morbidity and mortality.[26] Affected patients require periodical imaging to detect pulmonary alterations, such as acute inflammation, mucus retention, or development of bronchiectasis, and to monitor potential progressive lung parenchymal destruction and alteration.[4,11] Using CT for repetitive imaging over the years leads to an accumulation of substantial effective doses of ionising radiation, which should be avoided, particularly in children and adolescents. In recent years, several publications have shown that lung MRI is equivalent to CT in lung disease assessment and monitoring.[1,12,14,26–28]

Application of a 3D UTE sequence to assess airway disease in patients with cystic fibrosis has been shown to be equivalent to CT in detecting bronchial alterations, such as peribronchial thickening, bronchiectasis, or mucus plugging.[22] Furthermore, parenchymal alterations in terms of consolidations or mosaic patterns could be assessed in a far better way compared to conventional T1- or T2-weighted sequences. More advanced studies combining UTE sequences with hyperpolarised gas allow for combined structural and functional MRI that may be advantageous particularly for the follow-up of cystic fibrosis patients.[29]

Using the UTE sequence, mucus plugging can be depicted comparable to the T2-weighted respiratory-gated radial FSE sequences with fat saturation, which provide a good contrast for mucus plugs because of their inherent sensitivity for fluid (Fig 1).

For depiction of bronchial wall thickening and bronchiectasis, the UTE seems to outperform all conventional MRI

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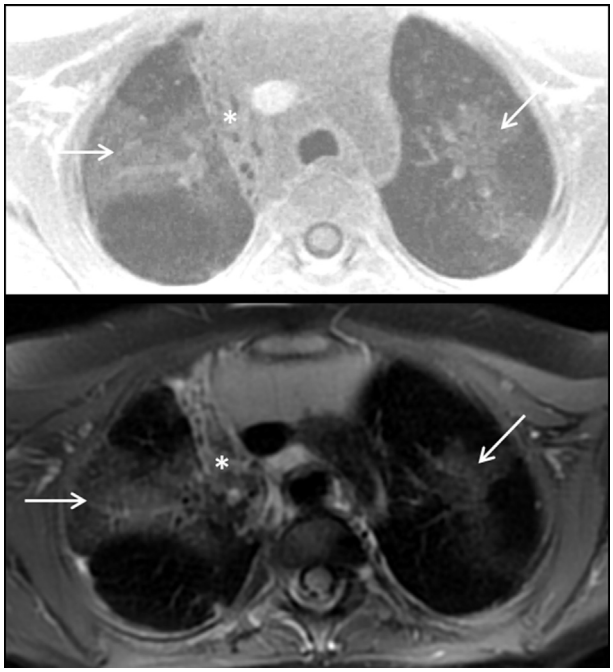

Figure 7 A 2-year-old female patient with bronchopulmonary dysplasia. Axial images obtained above the carina show a mosaic pattern with bilateral areas of ground-glass opacities (arrows) besides lung areas with low signal intensity and decreased lung markings. The appearance of atelectasis in the upper lobe (asterisks) most closely resembles that of CT (consolidation and air filled bronchi) on UTE images (at the top), while it appears as a more inhomogeneous pulmonary structure on fat-saturated T2-weighted radial FSE (at the bottom).

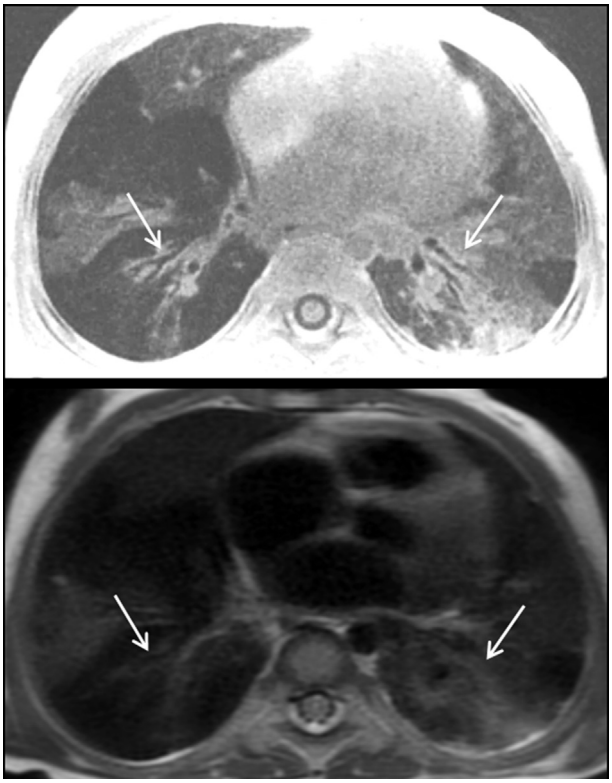

Figure 8 Axial images through the lower lobes in the same 2-year-old female patient with bronchopulmonary dysplasia as in Fig 7. The UTE (at the top) and SSFSE sequences (at the bottom) show a mosaic pattern bilaterally. Besides the ground-glass consolidations, bronchial wall thickening (arrows) is much better visualised by the UTE.

sequences, either with or without gating (Figs 2–4). Particularly for delineation of mild bronchiectasis and precise characterisation of more saccular or cylindrical bronchiectasis, the UTE sequence appears superior thanks to its increased contrast-to-noise ratio (Figs 2–4). In addition, associated centrilobular nodules and tree-in-bud patterns can be better visualised using the UTE compared to other sequences, which, in contrast, are frequently blurrier despite being fast non-gated sequences or techniques with motion correction or breath-hold (Figs 3 and 4). Consolidation is depicted by the UTE sequence comparably to other sequences (Fig 5).

Other chronic lung diseases

Pulmonary structural alterations, which partly overlap or resemble those of cystic fibrosis, occur in patients with interstitial pneumopathies. These patients also need regular follow-up imaging to monitor progressive disease.[4] In these patients, repetitive radiation should also be avoided; therefore, lung MRI would be the modality of choice. The superior contrast-to-noise ratio of the UTE sequence compared to the conventional MRI sequences allows for visualisation of interstitial fibrotic changes, bronchial wall thickening, bronchiectasis, and mosaic pattern resembling the image impression of CT images (Fig 6).

Preterm infants with respiratory distress syndrome are at risk of developing chronic pulmonary disease known as bronchopulmonary dysplasia. In the context of improved ventilation techniques and neonate care modalities, severe forms are less common now than in the past; however, there are still children who are impaired by the sequelae of their lung immaturity at birth and the concomitant treatment. In these cases, lung MRI is an excellent method to assess the extent of the lung disease. In a recent study, UTE achieved a higher signal of the lung parenchyma and fewer motion artefacts than standard 3D fast gradient recalled echo.[19] 3D Cones enables an excellent overview of the structural alterations, which manifest as segmental consolidation, areas of pulmonary over-inflation, ground-glass patterns, and bronchial wall thickening (Figs 7 and 8).

Pulmonary infections

Several publications in the literature show that the application of lung MRI for the characterisation of pulmonary infections, inflammation, and complications such as abscesses and empyema is feasible.[2,3,30] A comparative study for detection of paediatric lung infections using adequate MRI sequences and CT revealed that MRI performed comparably to CT in detecting thoracic abnormalities[30]; it was only inferior in depicting nodules <3 mm.

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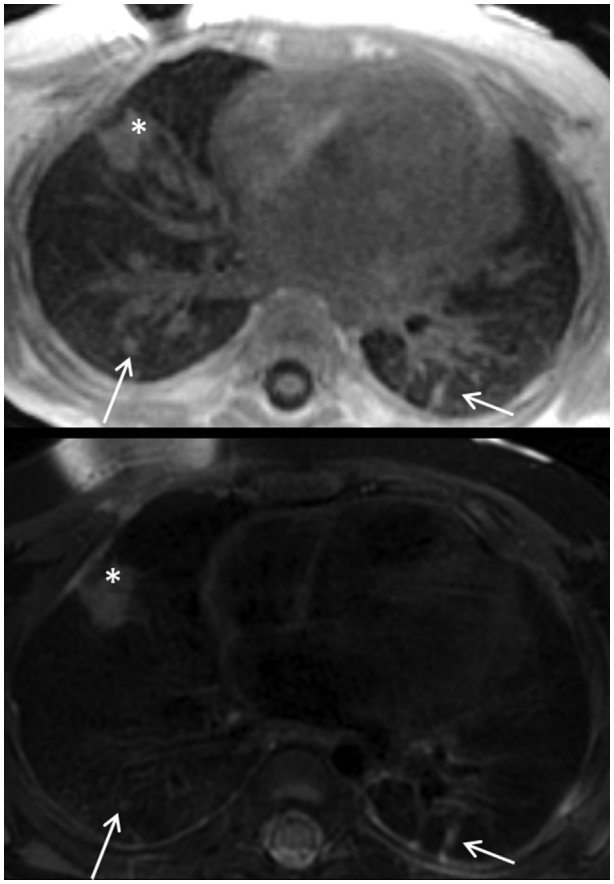

Figure 9 Axial images in a 1-year-old male patient with aspergillosis. UTE (at the top) is able to better depict small aspergillosis lesions (arrows) than conventional MRI (T2-weighted radial FSE). The large lesion in the right upper lobe (asterisk) is depicted equally well on the T2-weighted radial FSE sequence (at the bottom). Note susceptibility artefacts due to port-a-cath system in the right anterior chest wall.

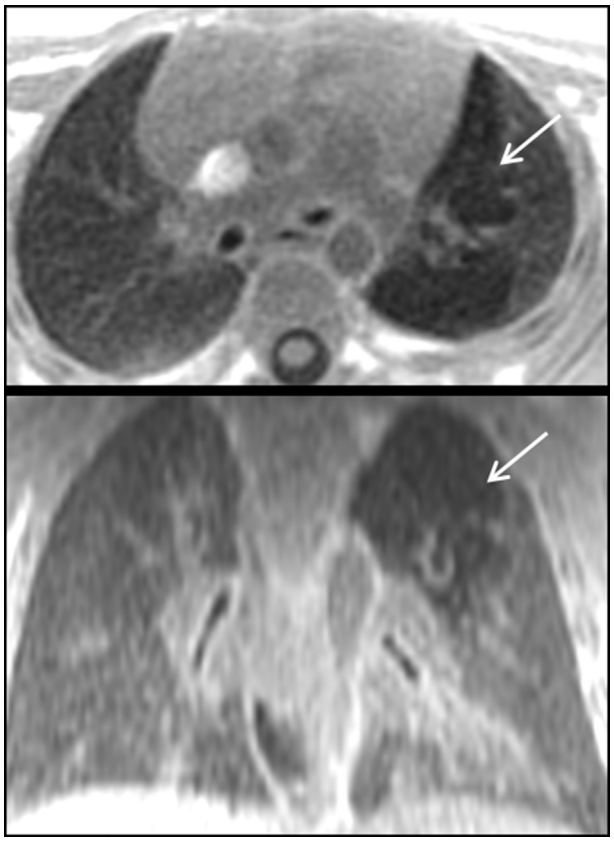

Figure 11 A 6-month-old female patient with congenital lobar overinflation of the left upper lobe. UTE (with coronal reconstruction) is able to show decreased intensity but normal parenchymal structure of the hyperinflated left upper lobe (arrows).

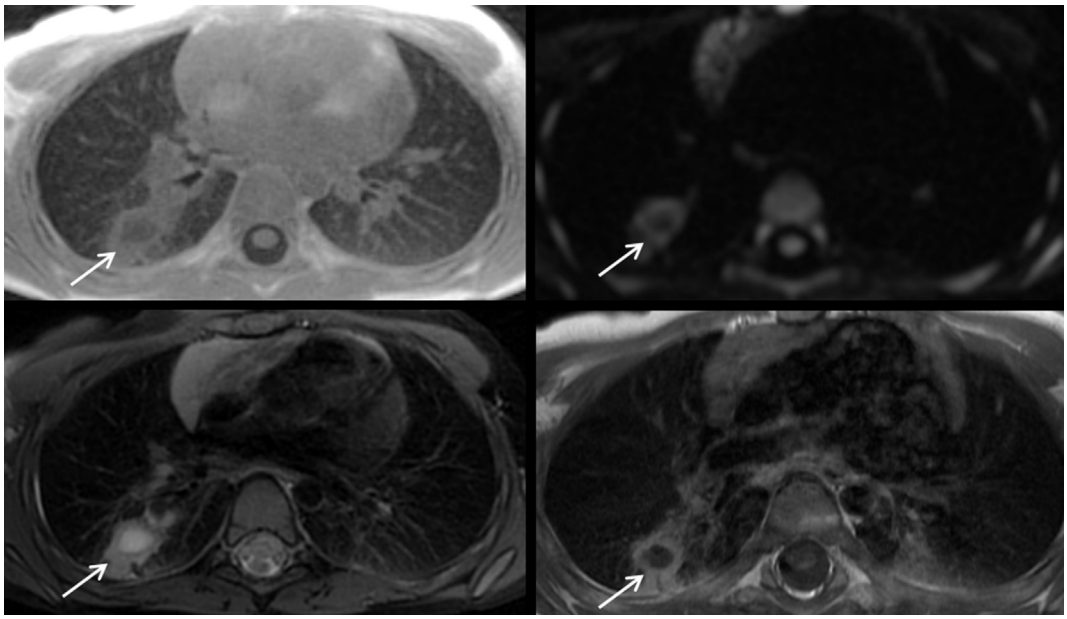

Figure 10 A 2-year-old male patient with cavitated pneumonia. The round, fluid-filled cavity (arrows) in the apical segment of the right lower lobe can be appreciated in the UTE sequence (upper right) as well as in the other sequences: DWI (upper left), fat-saturated T2-weighted radial FSE (lower right) and T1-weighted FSE sequence after contrast medium administration (lower left).

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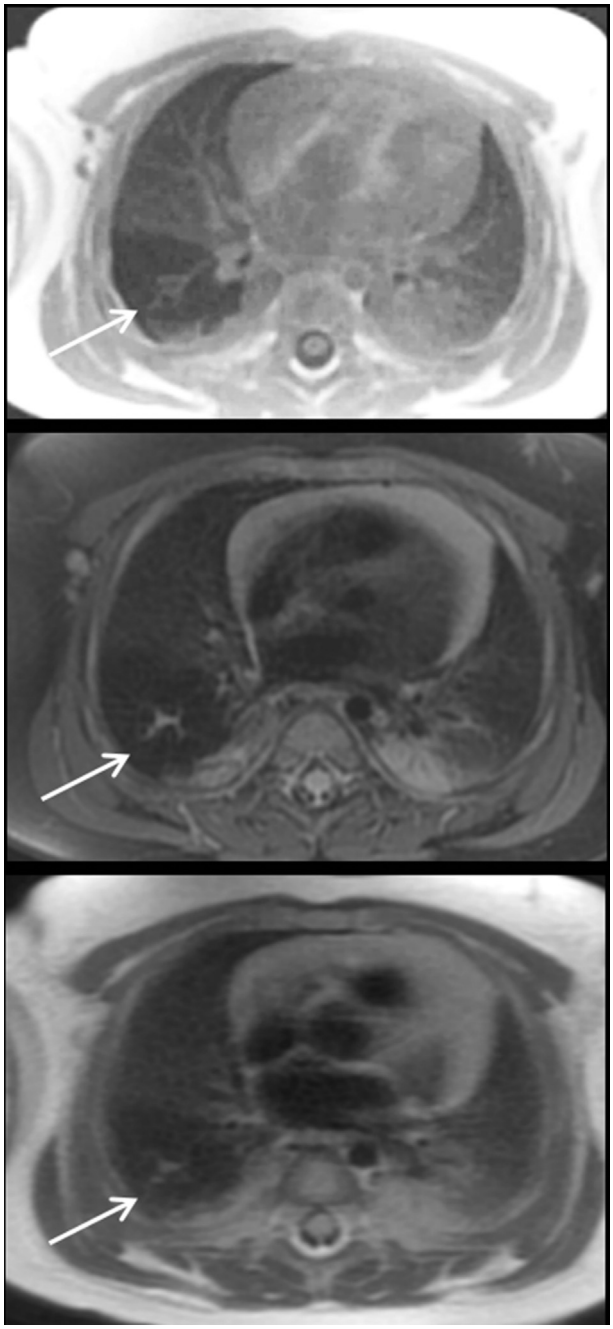

Figure 12 A 4-month-old male patient with segmental over-inflation in the right lower lobe. Conspicuity of the hyperinflated lung area (arrows) is superior on UTE (at the top) when compared to fat-saturated T2-weighted radial FSE (middle) or the SSFSE images (at the bottom).

Therefore, MRI can be considered a radiation-free alternative to CT when evaluating for pneumonia in immunocompromised children with increased radiosensitivity.[31] Lung MRI also showed promising results in children with allergic bronchopulmonary aspergillosis.[28] In our experience, the 3D UTE sequence outperforms other standard MRI sequences in detecting small nodules or consolidations such as in aspergillosis (Fig 9). In complicated pneumonia with cavitation, abscess formation, necrosis, or pleural empyema,

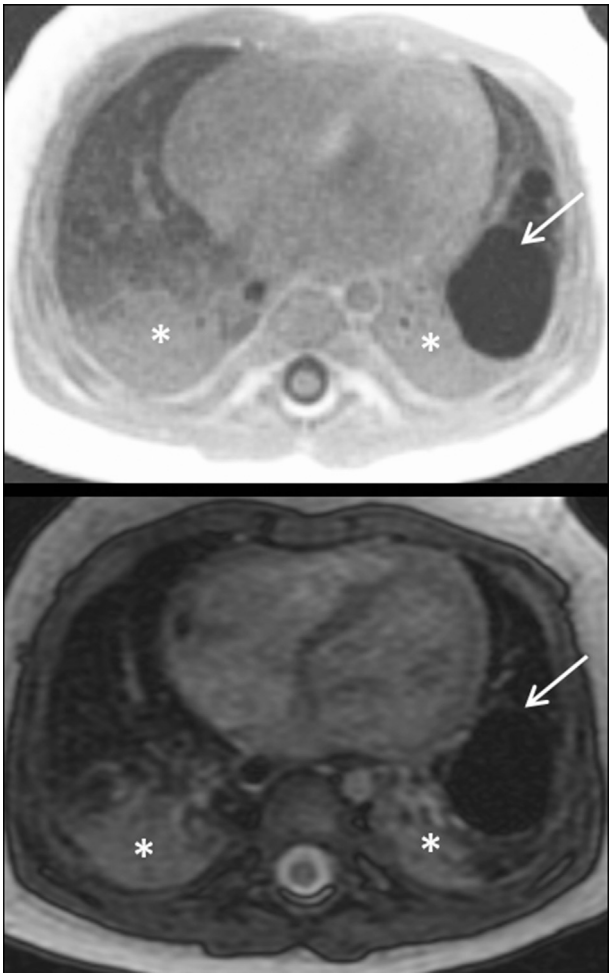

Figure 13 A 4-month-old male patient with congenital pulmonary malformation in the lingula. UTE (upper row) clearly discriminates a large cyst (arrow) and multiple adjacent smaller cysts, whereas the cystic nature of the lesion is less obvious on other sequences, shown for the bSSFP (lower row). Posterior atelectasis (asterisk) are equally depicted.

the accuracy of MRI has been likened to CT.[3] The above complications of pneumonia should also be evident on 3D UTE (Fig 10).

Congenital pulmonary malformations

Congenital lung malformations consist of several types of rare lung anomalies, including congenital pulmonary airway malformations (CPAM), bronchogenic cysts, bronchial atresia, bronchopulmonary sequestrations, and congenital lobar over-inflation.[32] CPAM is the most common congenital lung malformation (30–40%).[32] According to the current hypothesis, a malformation sequence based on airway obstruction during lung development seems to be the pathogenetic mechanism for various congenital lung anomalies.[33]

Hybrid lesions are defined as a combination of CPAM and bronchopulmonary sequestration.[32] Advanced diagnostic imaging is able to diagnose these lung lesions antenatally

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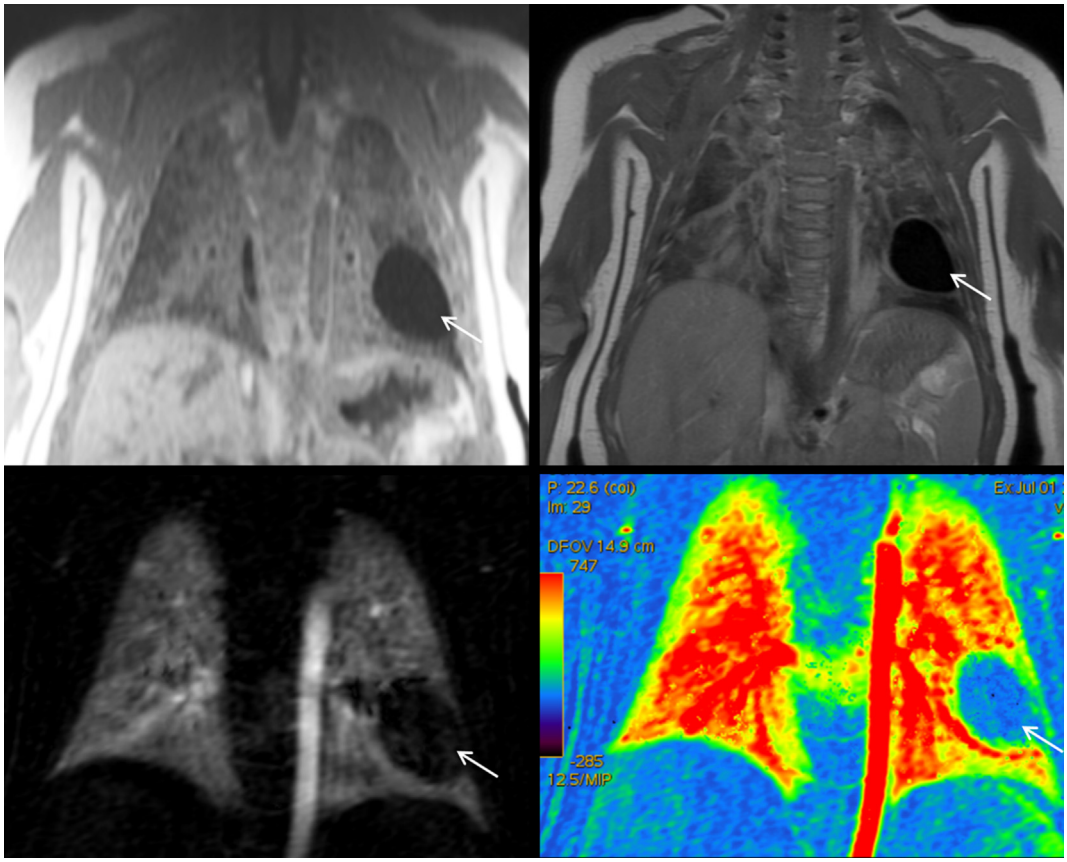

Figure 14 Coronal images of the same 4-month-old male patient with congenital pulmonary malformation as in Fig 13. Reformatted UTE (upper right) and PD-weighted FSE (upper left) images demonstrate the large air-filled pulmonary cyst, which does not show any enhancement on a subtraction image at peak enhancement (lowerright) and on a parametric image (lower left, enhancement integral during first pass) obtained from dynamic contrast-enhanced perfusion imaging.

and can also characterise symptomatic and occult congenital pulmonary malformations in postnatal imaging.[32] Prenatally detected lesions should be confirmed postnatally by CT or MRI, for characterisation of the lesion, planning surgery or as base line for follow-up of asymptomatic lesions.[13,34]

The UTE sequence allows for the detection of parenchymal lung abnormalities including abnormalities of aeration and perfusion in segmental or lobar hyperinflation and better delineation of cystic change in cases with CPAM or hybrid lesions compared to the other lung MRI sequences (Figs 11–14).

Conclusion

This review illustrates the ability of UTE lung imaging for assessing pulmonary disease in children. The respiratory-gated 3D Cones sequence can add to conventional lung MRI sequences by providing CT-like images with high spatial resolution. UTE MRI has the potential to provide detailed information on structural bronchial and parenchymal alterations, mainly in patients with cystic fibrosis, pneumopathies, infections, or congenital lung lesions.

Conflict of interest

The authors declare no conflict of interest.

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